King's Research Portal

DOI:

[10.1109/VTCSpring.2016.7504141](https://doi.org/10.1109/VTCSpring.2016.7504141)

Document Version

Peer reviewed version

[Link to publication record in King's Research Portal](#)

Citation for published version (APA):

Holland, O., Raman, A., Sastry, N., Wong, S., Mack, J., & Lam, L. (2016). Assessment of a platform for non-contiguous aggregation of IEEE 802.11 waveforms in TV white space. In *IEEE Vehicular Technology Conference* (Vol. 2016-July). [7504141] Institute of Electrical and Electronics Engineers Inc..
<https://doi.org/10.1109/VTCSpring.2016.7504141>

Citing this paper

Please note that where the full-text provided on King's Research Portal is the Author Accepted Manuscript or Post-Print version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version for pagination, volume/issue, and date of publication details. And where the final published version is provided on the Research Portal, if citing you are again advised to check the publisher's website for any subsequent corrections.

General rights

Copyright and moral rights for the publications made accessible in the Research Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognize and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the Research Portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the Research Portal

Take down policy

If you believe that this document breaches copyright please contact librarypure@kcl.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

Assessment of a Platform for Non-Contiguous Aggregation of IEEE 802.11 Waveforms in TV White Space

Oliver Holland, Aravindh Raman,
Nishanth Sastry, Stan Wong
King's College London
London, UK
{oliver.holland, aravindh.raman,
nishanth.sastry, stan.wong}@kcl.ac.uk

Jane Mack, Lisa Lam
InterDigital Communications, Inc.
Melville, NY, USA
{jane.mack, lisa.lam}@interdigital.com

Abstract—TV White Spaces (TVWS) and associated spectrum sharing mechanisms represent key means of realizing necessary prime-frequency spectrum for future wireless communication systems. We have been leading a major trial of TVWS technology within the Ofcom TV White Spaces Pilot. As one aspect of the work of our trial, we have investigated solutions for aggregation in TVWS and as part of that the performance of InterDigital White Space Devices (WSDs), capable of aggregating a IEEE 802.11 enabled technology for operation in up to 4 TVWS channels, non-contiguously as well as contiguously. This paper reports on some of our assessment of aggregation in TVWS, as well as our assessment of the InterDigital WSDs. It reports on the white space channel availabilities that can be achieved through aggregation, based on a real implementation of a WSD exhaustively testing a large area of England with a high resolution. The considerable benefit that is achieved through allowing non-contiguous aggregation as compared with contiguous-only aggregation is shown. Further, this paper assesses the TCP and UDP throughput performances of the InterDigital WSDs against the number of channels aggregated and received signal powers, in highly controlled scenarios. Statistics on performance of the WSDs for the studied large area of England are derived based on this. These results are compared with theoretical similar WSDs with one major difference that they can only achieve contiguous channel aggregation. Results show almost a doubling of capacity through non-contiguous aggregation with the InterDigital WSDs; this performance benefit would be increased significantly if more than 4 channels were supported for aggregation.

Keywords—TV white space, geolocation databases, field trials, spectrum aggregation, spectrum sharing

I. INTRODUCTION

Progress in TV White Spaces (TVWS) has been driven forward initially by significant regulatory steps and deployments in the US [1]. Europe is more recently following suit with its own rules for TVWS, and trials being undertaken based on those rules [2], [3]. The European rules for TVWS are quite different from the US, allowing variable maximum allowed EIRPs to be returned by geolocation databases (GLDBs), and one of five different White Space Device (WSD) transmission spectral mask qualities to be assumed, ranging for extremely strict to extremely lenient. These rules

are reflected in the ETSI EN 301 598 standard [2], defining the conformance requirements for WSDs and their operation. ETSI EN 301 598 is a Harmonized European Standard, implying the same such rules for TVWS realizations that transpire within any country in the EU.

We have been running a major trial within the Ofcom TV White Spaces Pilot [4], which is a key test of ETSI EN 301 598 in Europe. One major aspect of our trial is assessment of solutions for aggregation in TVWS, and the performance/potentials for aggregation. This aspect has been greatly facilitated by the development and loaning of experimental WSDs by InterDigital, USA to King's College London for testing. These devices include the capability of aggregating multiple IEEE 802.11 based channels in TVWS [5]. Training on the use of these experimental devices, and ongoing advice from InterDigital staff, have also helped greatly in this work.

This paper focuses on aggregation in TVWS, and particularly our trial assessing what can be achieved by aggregation in TVWS, as well as assessment of the InterDigital WSDs to verify that potential. A major aspect of this work is the additional gain that can be achieved through

Fig. 1. The InterDigital DSM IEEE 802.11 in TV white spaces experimentation platform.

(a)

(b)

(c)

(d)

Fig. 2. Availability of contiguous-only channels with at least 30 dBm Tx EIRP for a wide area of England, ETSI Class 3 WSD, 30m WSD height (darker areas indicate no availability): (a) 1 channel or more (i.e., where TVWS can be used at all for this configuration), (b) 2 channels or more, (c) 3 channels or more, (d) 4 channels or more.

non-contiguous aggregation, as is achievable with the InterDigital devices. A further aspect is the assessment of aggregation in general. Section II of this paper introduces the InterDigital WSDs. Section III assesses channel availability through aggregation, particularly showing the benefits of non-contiguous aggregation. Section IV assesses the throughput performance of the InterDigital WSDs, and derives performance statistics across much of England through merging with results obtained in Section III. This reinforces the benefits of non-contiguous aggregation. Finally, Section V concludes this paper.

II. THE INTERDIGITAL TV WHITE SPACE DEVICES

The InterDigital Dynamic Spectrum Management (DSM) TVWS IEEE 802.11 Demonstration Platform [5] (see Figure 1), which we have deployed at King’s College London, is designed to research, experiment with and demonstrate an implementation of a certified 802.11 protocol stack that has been modified to operate in TVWS. This system is capable of aggregating up to 4 contiguous or non-contiguous TVWS channels in order to maximize capacity. These devices were

designed to meet the Federal Communications Commission (FCC) requirements for license-exempt TVWS operation [1]. However, in collaboration with the expertise on the UK TVWS framework of King’s College London, the platform has been adapted to meet the operational requirements of the UK regulator Ofcom for usage in the UK [3]. This has enabled certification of the devices for UK use and participation of the equipment in the Ofcom TV White Spaces Pilot. Further, it is noted that the approach of Ofcom in the UK to TVWS has been adopted on the European level through the ETSI EN 301 598 Harmonized European Standard [2]—emphasizing the potential scope of increase in market for WSDs that are able to realize the characteristics of this framework.

Each of the InterDigital devices comprises a IEEE 802.11 MAC/PHY development board, a Digital Baseband Board (DBB) incorporating a “Sensing Tool Box” (STB), and two wideband digital radio boards. Each of the radio boards can cover a bandwidth of up to 48MHz and is capable of transmitting on up to 4 contiguous or non-contiguous channels individually or combined while ensuring that emission class requirements are not violated. The radio boards are referred to

(a)

(b)

(c)

(d)

Fig. 3. Availability of contiguous or non-contiguous channels with at least 30 dBm Tx EIRP for a wide area of England, ETSI Class 3 WSD, 30m WSD height (darker areas indicate no availability): (a) 1 channel or more (i.e., where TVWS can be used at all for this configuration), (b) 2 channels or more, (c) 3 channels or more, (d) 4 channels or more.

as the low-band and high-band boards, and respectively have been adapted from the devices' original US (FCC) TV band to support the UK (Ofcom) TV channel ranges of 26-36 (510-598 MHz) and 39-48 (614-694 MHz), with a 8 MHz raster. For the UK/EU case, it is noted that the WSDs have been developed and certified as being compatible with Class 3 spectrum mask requirements, as defined in ETSI EN 301 598.

The devices also each comprise a laptop computer, which on the AP side is interfaced to the modem over a serial interface and over Ethernet, the DBB/STA over Ethernet, and (optionally) the radio boards via USB. The laptop on the STA side is interfaced to the modem both by a serial interface and Ethernet. The serial connections on both sides, as well as the Ethernet interface to the DBB, are for control and monitoring purposes via the laptop. The Ethernet interfaces to the modem on both the AP and STA side are for user data traffic carrying purposes and additionally for control on the AP side. The devices typically run in a infrastructure-based topology, with one Access Point (AP) and one Station (STA) deployed for testing in our trials. The laptop computer associated with the AP has an application known as the Channel Management

Function (CMF) running on it. This interacts with the OFCOM web-listing of databases in order to choose an OFCOM approved GLDB that it will communicate with. The CMF will also command the sensing capabilities of the device and performs sensing if desired using the DBB/STB. Based on measurement input and GLDB information, the CMF will command the AP to dynamically allocate and aggregate the best available channels for transmission. Information on implementation requirements under the UK/EU framework is provided in [2], [3].

III. CHANNEL AVAILABILITY THROUGH AGGREGATION

First we assess channel availability for aggregation in TVWS for scenarios that are equivalent to the InterDigital WSDs' capabilities, namely, the aggregation of 4 or more channels. We have implemented a WSD at King's College London as part of our participation in the Ofcom Pilot, and we use that to query a white space GLDB at many different spoof locations, and transform/process the responses to obtain observations on performance. Results are all sampled/processed in steps of 0.01 degrees both in latitude

TABLE I: ACHIEVED AVERAGE RATE OF THE INTERDIGITAL DEVICES AGAINST NUMBER OF CHANNELS AGGREGATED AND RECEIVED SIGNAL STRENGTH

Received Signal Strength at Antenna (dBm per Channel)	No. of Aggregated Channels	Throughput (Mbps)	
		TCP	UDP
-61	1	6.2	8.2
-63	2	9.8	17.5
-64	3	14.7	24.8
-67	4	17.4	33.9
-64	1	6.2	8.3
-66	2	9.8	17.4
-67	3	15.1	26.2
-70	4	16.7	29.8
-67	1	6.2	8.2
-69	2	9.7	17.5
-70	3	15.1	26.0
-73	4	13.2	19.8
-70	1	6.1	8.2
-72	2	9.7	17.5
-73	3	12.7	20.0
-76	4	9.4	11.5
-73	1	6.2	8.3
-75	2	10.0	16.7
-76	3	9.6	12.5
-79	4	Failed	4.1
-76	1	6.2	8.3
-78	2	7.7	9.8
-79	3	0.2	3.5
-82	4	Failed	6.0

and longitude, for a wide area of England as seen in Figures 2 and 3. This area is of dimensions approximately 220 km by 190 km, almost 42,000 km². At the chosen sampling spatial frequency, this equates to 54,400 samples in total over that area. For the particular set of results reported in this paper, the WSD height above ground level is fixed at 30 m, and the spectrum mask of the WSD is Class 3.

Results in Figure 1 show the performance potential of contiguous aggregation, as would be appropriate for single-radio devices using a waveform such as contiguous OFDM. It should also be noted that only 5MHz of each 8MHz wide UK channel is utilized so that with 4 aggregated channels only 20MHz of the total 32MHz bandwidth is utilized for transmission resulting in the Throughput seen in Table I which can be further optimized by using more of the channel bandwidth and more significantly by aggregating non-contiguous channels. It is clear that as the number of contiguous channels aggregated increases, the proportion of locations in which that aggregation could be performed rapidly decreases. Presenting this in terms of numerical statistics, although 1 or more channel can be used in 98% of locations of this area of England, 2 or more, 3 or more and 4 or more contiguous channels can be aggregated in only 66%, 21%, and 14% of locations respectively.

In contrast, results in Figure 2 show the case where non-contiguous aggregation is also allowed, as might be achieved by the use of multiple radios as for the InterDigital equipment, or the use of novel waveforms such as Filter-Bank Multi-Carrier, or Non-Contiguous OFDM, among others. Here, the proportions of locations in which 2 or more, 3 or more and 4 or more channels can be aggregated are 89%, 82%, and 71% respectively.

This demonstrates the vast improvement in available TVWS bandwidth that is achieved through non-contiguous aggregation, e.g., as achieved by the InterDigital equipment. Moreover, it is noted that there is quite a high spatial variability in such availability, leading to the observation that even for the 4-channel aggregation case good downlink coverage might still be achieved in over 95% of the given area, through careful placement of base stations in locations where such aggregation can be achieved. If the necessary bandwidth were reduced to, e.g., a maximal bandwidth LTE carrier (20 MHz, equivalent to 3 channels being aggregated), then it would be possible to achieve good coverage in virtually every location. Further, on the uplink, if it is assumed that transmission power is reduced to 20 dBm—which is approximately equivalent to the case for mobile communications systems today—then it has been observed in other studies that 4 channels could be aggregated non-contiguously in all locations, and contiguously in 98% of locations (see, e.g., results for the London area in [6]; similar results extrapolate to larger areas of England). Although this emphasizes exceptional performance potential on the uplink, it is noted that interference from distant DTT transmissions that are not meant to be covering the area greatly influences this observation for above-rooftop receivers, generally leading to a much lower than expected SINR on the uplink [4]. This effect is due to the extremely high transmission powers of DTT stations (typically in the range of 100's of kW EIRP), the low powers of TVWS transmissions (up to 4W EIRP), and the good propagation in TV spectrum. Our past observations have therefore pointed to TVWS as being most suitable for downlink communications in mobile communication scenarios, or indoor communication scenarios [4].

IV. AGGREGATION USING THE INTERDIGITAL DEVICES

Here we assess the aggregation performance of the InterDigital devices. We deploy the equipment in controlled scenarios under a range of measured received signal powers, and assess TCP and UDP throughput performance for different numbers of channels being aggregated. It is noted that all performance results are achieved using iperf, with the end-node instances running on the laptops directly at each end of the TVWS link, thereby removing the spurious effects of networks and the Internet. Each assessment is over a duration of 30 seconds, with throughput results being averaged over that duration.

Table I presents the throughput performance of the devices against number of channels aggregated and various received signal strengths. It is clear that for UDP full-buffer throughput the devices can achieve marginally above 8 Mbps for each channel that is aggregated, and 6 Mbps for TCP traffic—although this reduces particularly for TCP traffic as the

number of channels being aggregated increases. This reduction is caused by a reduction in the transmitted power-per-channel of the WSDs as more channels are aggregated, deliberately implemented order to maintain linearity of the system. The effect of this on TCP is greatly amplified by uncontrolled packet loss due to lower transmission powers affecting congestion control.

In the UDP case, as long as the received power per channel is high enough to only lead to a small percentage of packets being lost as the number of aggregated channels increases, the UDP throughput is affected by only the percentage of that packet loss. Hence, UDP performance is observed to be almost proportional to the number of channels that are aggregated over a far larger range of received powers, only being severely affected for relatively low received signal powers.

These performances have been mapped to the locations in which the range of 1 to 4 channels is available for the devices, based on the assessments of the number of channels that can be aggregated in different locations as given in Section III. Results have been compared with a theoretical similar device to the InterDigital devices, the only difference being that this theoretical device can aggregate channels only contiguously. Moreover, it is assumed that the “gaps” between contiguous channels are used by the waveform, whereas for non-contiguous transmission only the 5 MHz signal bandwidth in each channel is used. This is equivalent to a 3 MHz bandwidth gain for each additional contiguous channel aggregated above 1 transmission channel, equivalent to a $3(\text{MHz})/10(\text{MHz})$ (30%) gain for 2 contiguous channels being aggregated, $6(\text{MHz})/15(\text{MHz})$ (40%) gain for 3 contiguous channels, and $9(\text{MHz})/20(\text{MHz})$ (45%) gain for 4 contiguous channels.

With this assumption of contiguous transmission “filling the gaps” between channels, the system could, on average, achieve a UDP throughput of 20.7 Mbps for contiguous only transmission over the area of England that is studied. This is based on the percentages of locations in which no channels, only 1 channel, only 2 contiguous channels, only 3 contiguous channels, and 4 or more contiguous channels can be used respectively being 2%, 32%, 45%, 7%, and 14%. Without this assumption of “gap-filling” (i.e., with only the 5 MHz signal bandwidth being used in each contiguous channel—which is currently the case for the InterDigital equipment if it is transmitting in contiguous channels), the system could achieve an average throughput of 15.9 Mbps. Comparatively, through non-contiguous aggregation in this area of England, the InterDigital devices would achieve a rate of 27.1 Mbps on average. This is based on the percentages of locations in which no channels, only 1 channel, only 2 channels, only 3 channels, and 4 or more channels being available as being 2%, 9%, 7%, 11%, and 71% respectively. Even assuming “gap-filling” in contiguous transmission, a 31% benefits of non-contiguous aggregation over contiguous aggregation is clear. Further, if it is not assumed that the contiguous channel waveform is able to “fill the gaps” between channels left by the 5 MHz bandwidths, then the average performance of non-contiguous aggregation using the InterDigital devices is 70% better than the contiguous aggregation case. This gain would be greater if the device were able to aggregate more than 4 channels.

V. CONCLUSIONS

This paper has considered a number of aspects of aggregation in TV White Spaces (TVWS), through real experiments within a pioneering trial of TVWS technology. The target of investigation is the white space devices developed at InterDigital in the USA, where the study of these is also supported by white space device capabilities developed as part of the UK/EU TVWS framework, and the assessment of white space availability based on those capabilities. Through assessing TVWS availability statistics for a large area of England, it has been shown that aggregation yields excellent performance potential, and that non-contiguous aggregation—as is achievable through the InterDigital devices considered in this paper—yields far greater performance than contiguous aggregation in a real world scenario. The performance of the InterDigital devices has also been assessed, in controlled signal conditions. This has been numerically mapped to TVWS availabilities in England in order to derive the expected performance of the InterDigital devices on average over the assessed area.

The work performed in this paper has shown the clear potential of TVWS, and moreover has shown what can be achieved through careful design of equipment and deployment scenarios for aggregation in TVWS. However, it is noted that in November 2015, the ITU World Radio Communication Conference (WRC) 2015 opted to assign the upper 96 MHz of the TV band in ITU Region 1 (which includes the UK) to mobile broadband on a co-primary basis—as had been expected based on the results of WRC 2012. Although this decision reduces the performance that can be expected in TVWS, it doesn’t ruin TVWS potential, especially for Classes 1 to 3 of white space device spectrum masks—noting that the InterDigital equipment achieves Class 3. A deeper assessment of the worst case results of this decision is available in [4].

ACKNOWLEDGMENT

This work has been supported by ICT-SOLDER, FP7 project number 619687, www.ict-solder.eu, and the ICT-ACROPOLIS Network of Excellence, FP7 project number 257626, www.ict-acropolis.eu.

REFERENCES

- [1] FCC, “In the Matter of Unlicensed Operation in the TV Broadcast Bands, Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band, Second Memorandum, Opinion and Order,” Sept. 2010 (see also Third MO&O from Apr. 2012).
- [2] ETSI, “White Space Devices (WSD); Wireless Access Systems operating in the 470 MHz to 790 MHz frequency band; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive,” v1.1.1, Apr. 2014.
- [3] Ofcom, “Implementing TV White Spaces,” statement, February 2015, accessible at <http://stakeholders.ofcom.org.uk/consultations/white-space-coexistence/statement>, accessed May 2015.
- [4] O. Holland, *et al.*, “To White Space Or Not To White Space: That Is The Trial Within The Ofcom TV White Spaces Pilot,” IEEE DySPAN 2015, Stockholm, Sweden, Sept.-Oct. 2015.
- [5] InterDigital White Paper, “Dynamic Spectrum Management”, accessible at http://www.interdigital.com/wp-content/uploads/2012/10/InterDigital-DSM-White-Paper_Oct2012.pdf, accessed Feb. 2015.
- [6] O. Holland, *et al.*, “Geolocation-Based Architecture for Heterogeneous Spectrum Usage in 5G”, IEEE Globecom 2015 Workshops, San Diego, CA, USA, December 2015.